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EVALUATION OF DESIGN CONCEPTS FOR COLLAPSIBLE CRYOGENIC STORAGE VESSELS

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ABSTRACT

Future long-duration missions to Mars using in situ resource production to obtain oxygen from the Martian atmosphere for use as a propellant or for life support will require long term oxygen storage facilities. This report describes preliminary analysis of design concepts for lightweight, collapsible liquid oxygen storage tanks to be used on the surface of Mars. With storage at relatively low pressures, an inflatable tank concept in which the cryogen is stored within a fiber-reinforced Teflon FEP bladder is an efficient approach. The technology required for such a tank is well-developed through similar previous applications in positive expulsion bladders for zero-g liquid fuel rocket tanks and inflatable space habitat technology, though the liquid oxygen environment presents unique challenges. The weight of the proposed structure is largely dominated by the support structure needed to hold the tank off the ground and permit a vacuum insulation space to be maintained around the tank. In addition to the inflatable tank concept, telescoping tank concepts are studied. For a telescoping tank, the greatest difficulty is in making effective joints and seals. The use of shape memory alloy to produce a passive clamping ring is evaluated. Although the telescoping tank concepts are a viable option, it appears that inflatable tank concepts will be more efficient and are recommended.

1 INTRODUCTION

Plans for future Mars missions propose using "in situ resource production" (ISRP) plants to obtain oxygen from the atmosphere for use as a rocket propellant and, in the case of manned missions, for life support [1]. Particularly if an extended program of human missions to Mars is begun, it will be necessary to develop oxygen storage facilities on the surface of Mars. For launch from Earth, such storage tanks must obviously be lightweight. In addition, to improve the efficiency of the launch packaging the tank should be collapsible. This report describes the preliminary analysis of various design concepts for collapsible liquid oxygen storage tanks to be used on Mars. Dr. Eric Thaxton and other personnel at NASA Kennedy Space Center developed the foundations for the design concepts. While no specific mission is followed for this design study, the capacity of the tank and other design requirements are loosely based on the oxygen requirements for a manned Mars mission as described in the NASA Reference Mission [1,2]. To the extent possible the work is presented in a general fashion to permit appropriate scaling to be conducted for missions with different requirements. Detail design must wait until a specific mission with specific requirements is planned.

2 PREVIOUS RESEARCH

While there has been a substantial amount of research on ISRP, particularly for oxygen production on Mars and the Moon, relatively little attention has been paid to storage requirements and tankage. The NASA Mars Reference mission [1,2] assumes that produced oxygen will be fed directly into flight tanks on an ascent vehicle. Mueller and Durrant [3] discuss storage issues for a proposed Mars sample return mission using this storage concept. However, if a prolonged series of Mars missions is begun, or for different mission architectures, it may be more efficient to provide long-term storage tanks on Mars separate from vehicle flight tanks. Mars oxygen storage tanks will be substantially different from conventional terrestrial storage tanks or even ordinary flight tanks. However, previous engineering experience with collapsible pressure vessels, lightweight fluid storage tanks and inflatable space structures is relevant to the design of a collapsible cryogenic storage tank for Mars and is reviewed here.

ILC Dover Inc. developed a collapsible hyperbaric chamber with an interior roughly the size of a person, designed for a burst pressure of 6 atm [4]. The design uses a "bladder layer" of urethane-coated polyester to contain the gas with a "restraint layer" made of polyester webbing/polyester fabric to resist the mechanical loads. For mobile, lightweight storage of petroleum products the military uses collapsible bladder tanks. These tanks, made of fabric-reinforced elastomers, take the form of fluid-filled pillows and are available in capacities ranging up to the hundreds of thousands of gallons [5]. Flanagan and Hopkins [6] proposed a similar concept for water storage during human missions to the Moon or Mars. This tank is a simple bladder made of parachute nylon with a plastic liner. A prototype of such a 100 gallon capacity tank weighed about 1 kg (2.2 lb_m). Inflatable space structures using similar principles for containing pressure have been developed or proposed for a variety of applications [4,7]. A recent development in inflatable space habitats is Transhab, developed at JSC and proposed for either long duration space flight or as a space station module [2,4]. Transhab uses triple redundant Kevlar reinforced membranes to form the main pressure barrier and a flexible outer layer for meteor impact protection and insulation. The net thickness of the wall is about one foot. An alternative to inflatables for collapsible space habitats and modules is telescoping rigid structures. Although this concept has not received as much attention as inflatables, at least one NASA design study [8] explored the idea. In this study a two-stage telescoping arrangement for a space station module is proposed.

3 DESIGN FUNDAMENTALS

Barron [9] describes the fundamentals of the design of conventional cryogenic storage vessels. An inner vessel supports the weight of the cryogen and the associated pressure. To insulate the vessel either a vacuum space or vacuum-filled insulation is provided around the inner vessel. An outer pressure vessel contains the vacuum. A suspension system must be provided to hold the inner vessel within the outer vessel while minimizing the heat loss through the insulation space. Supports must be provided to hold the vessel. Finally, the necessary piping and fill lines must be included. Each of these basic tank components must be provided in the Mars liquid oxygen tank. Due to the mission requirements, however, the nature of these components may differ considerably from those of a conventional earth tank. Design requirements for a Mars liquid oxygen storage tank were chosen to provide a basis for evaluation. The tank must be capable of continuous operation for several Earth years and is sized to carry a mass

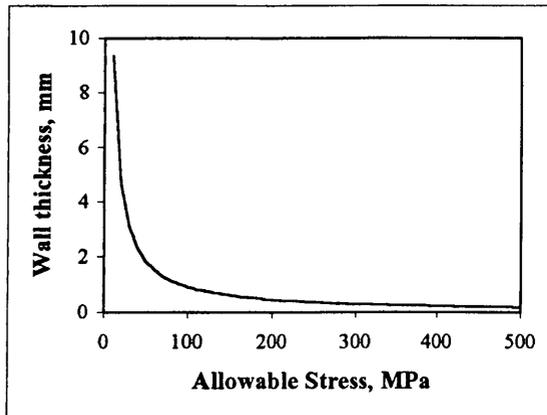


Figure 1 Minimum wall thickness for the inner vessel as a function of the allowable stress

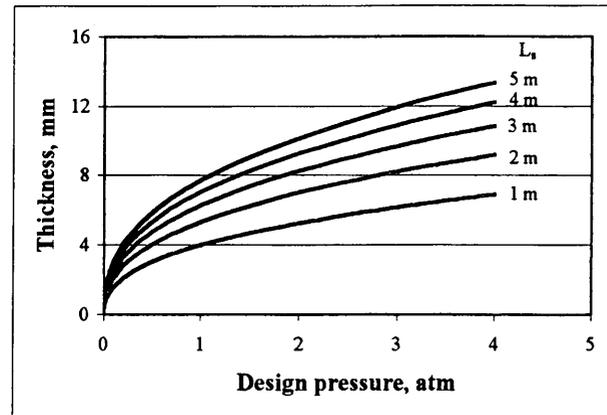


Figure 2 Minimum wall thickness for the outer rigid vessel as a function of the design pressure for various unsupported lengths

of 50,000 kg (110,000 lb_m) of liquid oxygen. The tank will hold a saturated liquid at 79 K (142 R) and 276 millibar (4 psia) ullage pressure. For launch packaging it is assumed an inside diameter for the tank of nominally 10 ft (3m) will be acceptable.

The pressure tank (“inner vessel”) will operate under the pressure of the oxygen vapor and the weight of the liquid oxygen. The head pressure of the liquid oxygen is 44.5 millibar per meter (0.197 psi per foot), considering the density at the operating temperature and the reduced gravity of Mars. For typical tank geometries achieving the required volume, the limit pressure is under 700 millibar (10 psi). This relatively low operating pressure of the tank will be a fundamental driver of the designs considered here. Equation 1 is the minimum thickness, t_{min} , based on static strength required by the ASME code [12]. p is the design pressure, D is the diameter of the shell, s_a is the allowable stress and e_w is the joint efficiency (assuming welded joints). Figure 1 shows the required wall thickness

$$t_{min} = \frac{pD}{2s_a e_w - 1.2p} \quad (1)$$

as a function of the allowable stress for the assumed loading and cylindrical geometry and assuming a perfect joint efficiency. For typical engineering materials the required wall thickness is small, 1 mm (4 mils) or less. These small wall thicknesses are similar to those of flight tanks in early spacecraft, such as the pressure stabilized Atlas vehicle [10]. If the Mars storage tank is built to minimum dimensions it, too, must act as a pressure-stabilized structure, ineffective in supporting out-of-plane stresses that might be experienced while unpressurized. However, since considerable lateral loads may be anticipated during launch and landing it is likely that a rigid walled structure would require additional reinforcement. This would make its weight greater than would be required from the pressure loading alone. A flexible inflatable tank wall avoids this problem and can therefore be designed closer to its optimum weight.

Although the Mars atmosphere exists in a condition that is categorized as “Medium Vacuum” [9], this level of vacuum is insufficient from an insulation standpoint [3,11], and thus high vacuum must be drawn in the insulation space. If this vacuum is drawn on Earth (which would offer significant simplifications in the design of the vacuum system) a rigid outer vessel must support 1 atm of pressure. If vacuum is drawn in space (by venting of the insulation during flight [3]) or on Mars, then only the pressure of the Mars atmosphere (about 12 millibar or 0.2 psi, depending on the location on Mars [12]) must be supported. Required thickness for an assumed cylindrical rigid outer vessel is based on the short cylinder collapse formula shown in Equation 2 [9]. p_c is the collapse pressure, E and ν are the modulus and Poisson’s ratio for the assumed isotropic shell, D is the diameter, L is the unsupported length of the cylinder, and t is the wall thickness. For a modulus of 200 GPa (steel), the required thickness is plotted in Figure 2 as a function of the design pressure for various unsupported lengths, L . The required shell thickness to

$$P_c = \frac{2.42E(t/D)^{5/2}}{(1-\nu^2)^{3/4}[(L/D) - 0.45(t/D)^{1/2}]} \quad (2)$$

support Earth's atmosphere is over 5 mm for reasonable values of unsupported length and factor of safety. Because the required wall thickness scales approximately as $p^{2/5}$ designing the outer shell to resist only the pressure of Mars results in a factor of 6 improvement in thickness (and therefore weight) of a rigid outer shell with equal unsupported length, L . However, even considering the low surface pressures, a rigid pressure wall for the outer shell is not the most effective design. If the insulating material can react either the full atmospheric pressure of Earth or the slight atmospheric pressure on Mars without damage or reduction in its thermal properties, then the outer wall may be made from a flexible material or a thin foil [3,11]. Not only is this approach very lightweight, it is also very well aligned with the objective of making a collapsible vessel.

Flynn [13] discusses materials for suspension system components. Glass/epoxy composites offer about a factor of 20 improvement over stainless steel in conductivity to strength and about a factor of 4 improvement over stainless steel in conductivity to stiffness. Several applications of composite supports in cryogenic space vehicle tanks are summarized in References 14 and 15. There are two primary configurations for composite supports: struts and straps. Strut supports connect the inner tank to the outer support through pin-ended axial members that can support tension or compression loads. Strap supports operate exclusively in tension. A typical strap design uses two sets of 6 straps pulling in opposing directions. Pretension is included in the straps on installation such that all straps maintain tension throughout the full range of loading. For the collapsible tank concepts studied here maintenance of pretension in the straps is difficult. Also, the need for significant separation between the sets of straps would require excess mass in the support structure. Hence struts are considered exclusively in the designs that follow. Launch and landing loads may be a limiting factor for the suspension system. Lateral loads and g -loading in the vertical direction will be largest during launch or landing. Because of the nature of this study, there is no particular launch vehicle to be considered for the design, nor is the landing method specified. Therefore, launch and landing loads are not specifically addressed. To constrain the tank structure during flight without requiring additional mass in the suspension system, external attachment to the piping structure in the rigid end cap should be used. It is assumed that the tank piping is not connected during flight and adding a temporary mechanical attachment through the piping should not present any serious obstacles. Stabilizing the empty and collapsed structure against damage due to vibration during flight is also a significant concern for launch packaging.

Unfortunately, the tank cannot rest directly on the ground, as do the pillow bladder collapsible fuel storage tanks [5]. Most of the structural mass of the proposed Mars tank designs is associated with the support structure. The support structure must hold the effective weight of the cryogen (190 kN, or 42 kip) above the Martian surface and permit attachment with the suspension system. Installing the tank in a vertical orientation eliminates the bending moments that would be associated with a horizontal orientation and the use of cradle supports. Contact with the surface will be made through leg structures. The use of skirt supports or other vertical tank supports commonly used on Earth is impractical due to the fact that the tank must be placed on an unprepared, rocky surface. Design of the legs is assumed to be essentially similar for all tank concepts and is not addressed in detail. Wind and seismic loads should be considered in the design of support structure for a storage tank design. Although the winds on Mars can be severe, the low density of the atmosphere keeps the dynamic pressure small. A conservative calculation results in a maximum drag on the entire tank of about 900 N (200lb_f). Dynamic effects due to wind loading may be relevant, considering the pressure-stabilized, flexible nature of several of the structural concepts. In the unfilled or partially-filled state wind loading could produce a rippling effect that may degrade flexible materials at cryogenic temperatures. Current scientific belief is that there is some seismic activity on Mars, perhaps more than on the moon but less than on the Earth [12]. Seismic loading is not addressed further in this design study, though future detailed design will need to consider seismic effects.

Two primary concerns relating to material selection for the tank are oxygen compatibility and performance at cryogenic temperatures. Oxygen compatibility is discussed in NSS-1740.15 [16]. Collapsible tank concepts suggest the need to use nonmetallic materials. Although the choices for oxygen compatible nonmetallic materials are

somewhat limited fluorinated polymers, such as Teflon FEP, are acceptable. Ceramics and glasses are considered inert in the oxygen environment. The use of composite materials for liquid oxygen tankage seems problematical because the polymeric materials typically used as matrix materials are flammable and likely sensitive to impact in a liquid oxygen environment. However, there have been some successful developments in the use of composite materials for liquid oxygen tanks either using coatings [17] or proprietary oxygen compatible matrix materials [18]. Typically, the ultimate tensile strength of a solid material increases with reduction in temperature [13]. This trend applies as well to composite materials. Some plastic materials retain ductility at cryogenic temperatures. Among these are several grades of Teflon, including FEP, though their elongation at cryogenic temperatures is nowhere near their room temperature properties. For materials used as a membrane for containing the liquid oxygen or for the vacuum insulation shell, permeability is another important property. Among the fluorinated polymer grades, FEP is recognized as having superior impermeability [19,20]. The inclusion of metallic films in Teflon membranes can improve their permeability [20].

4 INFLATABLE TANK DESIGN

The basic inflatable design concept is illustrated in Figure 3. A pressure membrane with flexible reinforcement contains the liquid oxygen. A flexible vacuum jacket containing insulation covers the outer wall of the pressure membrane. To facilitate piping and to support the weight of the stored contents, a rigid structural floor supports the lower portion of the pressure membrane. A suspension system support the weight of the tank through connection between this structural floor and an external support structure. Legs support the external support structure. Preliminary design of each of the tank components follows.

The pressure membrane serves the dual role of containing the cryogen and resisting the pressure loading. Fluorinated polymers, such as Teflon FEP, are perhaps the only suitable engineering materials for containing the cryogen. However, the strength of Teflon FEP alone is relatively small. The specific strength of FEP film at the required temperature is two orders of magnitude below what can be achieved with high strength materials such as Kevlar. The pressure membrane will thus be comprised of two parts, the "bladder" which must contain the cryogen and limit leakage and permeation, and the "reinforcement" which supports the mechanical loads. The technology required to produce such a pressure membrane made of a flexible bladder with filamentary reinforcement is well within reach of current technology. Teflon-coated fabrics are used in architectural applications [21]; flexible pressure membrane were used in the Transhab space habitat [4]; and large, seamless Teflon bladders have been

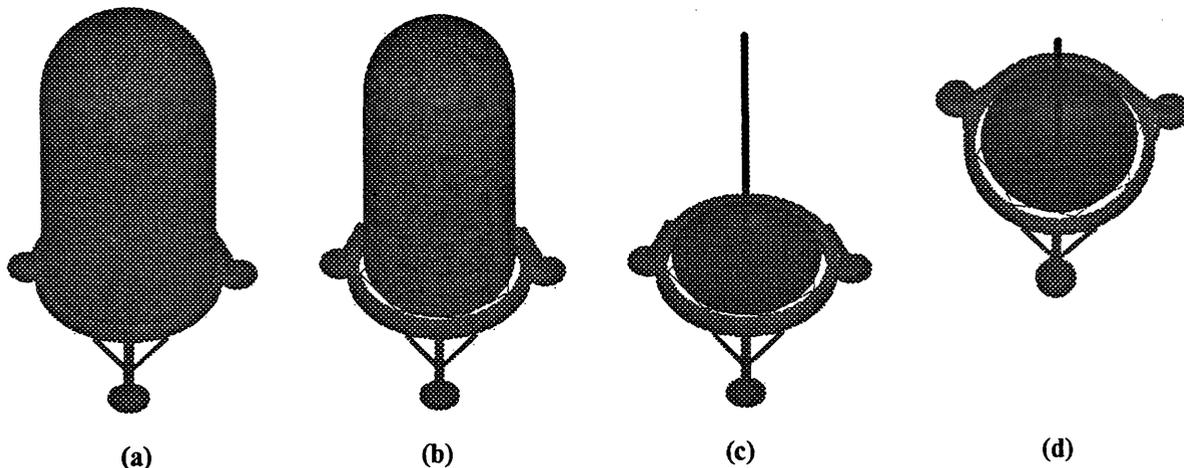


Figure 3 Schematic of the inflatable tank concept emphasizing (a) the flexible insulation membrane, (b) the pressure membrane, (c) the support structure including a rigid end cap, external support structure and legs, and (d) the suspension system (dark lines connecting the endcap to the external ring)

used as “positive expulsion bladders” in liquid fuel rockets [19,20]. For the Mars liquid oxygen tank bladder a 6 mil thick Teflon FEP bladder with an aluminum film embedded inside through a chemical vapor deposition (CVD) process is proposed. The mass loss due to permeability for this bladder is estimated to be on the order of 1 g/day (not including leaking at seals around the piping). Repeated folding and unfolding of the bladder is undesirable because it will degrade its impermeability. Further, because of the reduced flexibility of the material at cryogenic temperatures, it is undesirable to fold the material in the cryogenic state. Therefore, the tank must be inflated before cryogenic material is placed in the tank, and positive inflation must be maintained throughout its service life. There are various possible methods for reinforcing the bladder including fabric reinforcements, or more widely-distributed mesh or cable reinforcement schemes [4]. Due to the weakness of the bladder material at cryogenic temperatures, widely-spaced, discrete reinforcement bands will not be an effective solution. The best material to use for the reinforcement will be the flexible material compatible with the environment that has the highest specific strength. Advanced fibers are therefore superior to metal reinforcements such as stainless steel wire. Kevlar would be a logical choice for the reinforcement due to its high strength and excellent flexibility. However, it is not oxygen compatible, and thus, glass fiber reinforcement is recommended. Assuming that fibers are independently placed in the hoop and longitudinal directions average thicknesses of fibers in the hoop direction of 0.1 mm and in the longitudinal direction 0.05 mm are needed, for a total reinforcement thickness of about 0.15 mm. This is a typical thickness for a single, thin ply of fiberglass cloth. Similar quantities of material result from optimized placement of fibers using an off-axis, angle-ply arrangement. Although the diameter is rather large it would be beneficial to use a braided construction for the reinforcement in the cylinder to avoid joints in the hoop direction.

The total mass of one pressure membrane is about 38.7 kg (85 lb_m). To provide system redundancy, multiple bladder/reinforcement layers may be used, as in the Transhab design [4]. The weight penalty for including a redundant membrane is not very severe when the mass of other system components described below is considered. The inflatable tank concept is a pressure-stabilized structure. “Rigidizable” structure concepts [22] can potentially be used to make the pressure membrane rigid following inflation. This would help avoid problems with flexing of the bladder due to external loads such as wind, though care must be taken with regard to oxygen compatibility or the rigidizing agent.

For an insulation system compatible with the inflatable tank concept, the insulation will be contained within a double-walled flexible membrane. The insulating material is assumed to be “layered composite” type, with an approximate thickness of 25-40 mm (1 to 1½ inches), and a density of 52 kg/m³ [11]. Sizing of the vacuum membrane walls will be determined based on permeability. Similar technology to that used for the pressure membrane bladder may be used for the vacuum membrane. Due to the double-walled construction and the need to fill the interior with vacuum insulation, it may not be possible to form the vacuum membrane using seamless construction, and considerable care will be necessary to form effective and durable joints for the vacuum membrane. The mass of the insulation is estimated to be 138 kg (304 lb_m). The vacuum membrane material is estimated to be

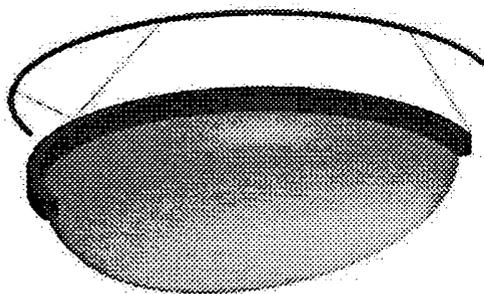


Figure 4 Ring girder support arrangement for lower endcap

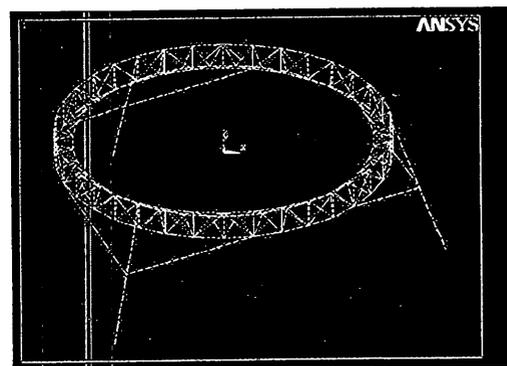


Figure 5 Truss structure for external support

about 40 kg (88 lb_m). Additional outer wall materials may be needed for impact protection, to resist abrasion from the Martian atmosphere, and to provide a reflective surface to limit radiation influx. Impact protection may be especially critical due to the requirement for vacuum insulation. Any impact that penetrates and causes leakage of the vacuum shell will effectively destroy the functionality of the tank. Because similar outer layers may be used for all tank concepts, detailed weight analysis is not made.

As discussed above, a composite strut suspension system is the most appropriate for the present application. The total mass of a six struts suspension system for the inflatable tank is small due to the tensile nature of the loading condition. The mass of the struts is estimated at 5.6 kg (12.4 lb_m), not including connections. The support structure is one of the most highly loaded components of the system. The pressure membrane alone is incapable of supporting concentrated loads such as are introduced through the suspension system or the structural legs. A rigid endcap will therefore be used to transfer load from the pressure membrane to the support structure. Although a rigid semimonocoque floor was considered for the lower endcap, a lighter alternative is to support the tank structure through a “ring girder” [23], as shown in Figure 4. This is a circumferential ring on the outside of the tank at the position of the junction between the lower endcap and the cylinder wall. A thin, metal lower end cap can be welded to this ring, and thus membrane stresses in the lower endcap will be transferred directly into this ring. A ring girder design that provides the necessary strength (assuming three vertical attachment points for the suspension system) is an aluminum hollow rectangular section with outside dimensions of 4×6 inches and a ¼ inch wall thickness. The mass of the ring of these dimensions is 81 kg (179 lb_m). Additional mass is required for the lower endcap, which can be fabricated at the minimum thickness required for a shallow ellipsoidal endcap. To accommodate the thickness of the suspension system, a “bulge” of extra insulation of about 20 cm (8 inches) thickness is required for the approximately ½ meter vertical height of the suspension system. This will result in extra insulation mass of about 52 kg (115 lb_m). An external support structure is needed to bear the load from the suspension system and pass it to the ground through the legs. Because the external support structure is outside the insulation space, the need for compactness is reduced, and a truss structure in the shape of a ring may be used. Estimation of the weight of such a structure for one possible configuration is based on the ANSYS model shown in Figure 5. The resulting structure, assuming graphite/epoxy composite members, has a mass of under 100kg, not including the joints. This analysis should be considered as preliminary as the suspension system configuration assumed for the model is different from what was ultimately selected and the truss configuration is not optimized. The total mass of the external support structure is estimated to be about 150kg.

Mass estimates for all of the system components for an inflatable Mars liquid oxygen storage tank are summarized in Table 1. The total mass of the tank not including legs, external impact protection, piping, or necessary systems such as vacuum pumps and cryocoolers is about 570 kg (1250 lb). The mass of the legs will be substantial, but the end result is likely to be a structure of less than one metric ton in mass.

5 TELESCOPING TANK DESIGN

A potential advantage of a telescoping arrangement for the Mars tank is the ability to use rigid structures. Minimum gage wall thickness can be used (with additional support necessary at the points of load application through the suspension system, as in the inflatable tank concept). However, extra rigidity may be needed to prevent damage of

Item	Mass	
	kg	lb _m
Pressure Membrane (2)	78	170
Insulation Membrane Walls	40	88
Insulation Material	190	419
Ring Girder and Cradle	100	220
Suspension Struts (6)	10	22
External Support Truss	150	330
Total (not including piping, legs, and mechanical systems)	568	1249

Table 1 Mass of components of inflatable cryogenic storage tank

the small thickness components during manufacture, flight and landing. Because design of the rigid inner vessel walls is conventional it will not be considered in detail. Rather, issues pertaining to joints, sealing, and integrating the vacuum insulation into the design will be explored. For the analysis here, it is assumed that the insulation is contained within a flexible “bag” which the telescoping structure will expand into, which simplifies the design of the joint.

Joints are the primary difficulty of a telescoping pressure tank. Not only must a mechanical joint be made between segments to restrain the longitudinal loads, the joints must also be sealed against leakage of the cryogen into the vacuum space. Locking rings operating on a principle similar to that used, for example, in autoclave doors may be used for this purpose, though external mechanism will be needed for actuation. An alternative means of clamping is through a shape memory alloy (SMA) locking ring proposed by Dr. Eric Thaxton. This concept uses the shape memory effect to make seals between segments in a cylindrical telescoping tank in a fashion similar to “Cryofit” fasteners, a commercial product used for joining high-pressure hydraulic tubing. A schematic of the concept is provided in Figure 6. The SMA locking ring is sized to be initially slightly larger than the telescoping segments it is intended to join. Upon heating above its transformation temperature the SMA locking ring experiences a phase change resulting in the reduction of its rest diameter below the diameter of the cylinder segments. Constraint provided by the cylinder structure produces clamping pressure between the segments. Because of the large diameter and thin walls of the cylinder segments, a back-up structure must be provided on the inside of the tank at the position of the SMA locking ring to avoid buckling. Preliminary sizing of a SMA locking ring for the present application is based on Nitinol material properties. However, due to the substantial amount of titanium in Nitinol it is questionable whether Nitinol alloys are oxygen compatible. Copper-based SMAs should be considered for this application [24]. A nominal design for a SMA locking ring has a cross-sectional area for the SMA ring of 422 mm² (0.65 in²), which is sufficient to resist the longitudinal pressure loading through friction alone. An aluminum back-up ring with a W6×15 wide flange I-beam shape is sufficient to prevent buckling. This design results in a mass of 26 kg (57 lb_m) for the SMA ring and 75 kg (166 lb_m) for the backing ring. The system mass for one SMA joint is therefore 101 kg (220 lb_m), not including the mass of the mechanical stops or systems for activating the shape memory effect. While the SMA locking ring concept offers a simple joint design with few mechanical parts, there must be a system for activating the shape memory effect. Activation is initiated by heating the ring. The energy required for activation is between 1325 kJ and 2480 kJ, neglecting losses, which may be substantial.

Designing effective seals for the telescoping segments is a challenging problem. Dimensional tolerances in the large diameter, thin-walled cylinder will likely precluding forming effective O-ring seals around the hoop direction. Conventional static face-type seals could be used on the mechanical stops of telescoping tank segments, as illustrated in Figure 6. Pressure in the tank or residual pressure from deployment and clamping of the joints will compress these seals. If pressure alone is relied upon for sealing, loss of pressure in the tank, even temporarily, will produce failure of the seals. For this reason, either a positive locking mechanism for the tank or redundant seals must be used. The problem of sealing can be greatly simplified by the use of a flexible bladder to contain the cryogen inside a telescoping tank. Then, the mechanical joints will carry only the pressure loading and will not be depended upon for sealing (except as a backup). The same sort of bladder used for the inflatable tank concepts can be used in this application. If a SMA locking ring is used it will produce a sealing effect through metal-to-metal contact between the cylinder segments. The sealing principle is similar to that of metallic gaskets in which a soft metal is compressed between two harder flanges. For flat metallic gaskets, soft aluminum requires the lowest seating stress at 60–70 MPa (8800–10000 psi) [25]. Corrugated aluminum may allow seating stresses of as low as 1000 psi. Achieving such clamping pressures over the whole face of the proposed SMA locking ring system is problematical due to the structural stability of the structure. However, if relatively narrow cylindrical rings of metal gasket material are placed between the cylinder segments that are being joined, high clamping pressure in the gasket material is possible. For the nominal SMA locking ring design above, a gasket width of 2mm corresponds to an effective contact pressure in the gasket of 60 MPa (8800 psi). This width is small, and deformation effects may reduce the clamping pressure. Generating effective seals in the SMA ring joint may require larger and heavier components than in the baseline SMA joint design. An alternative is to use a flexible gasket material (Fluoropoly 36, for example) between the cylinder segments. Keeping this gasket material in position and avoiding damage to it during tank extension will be a significant challenge.

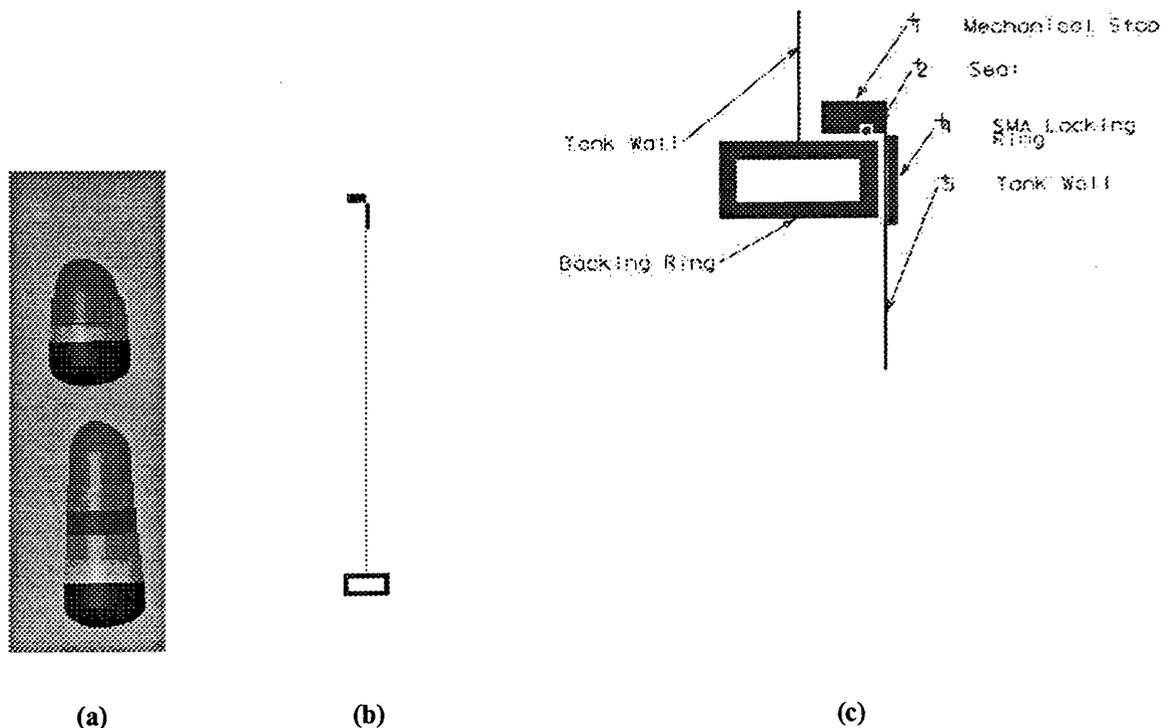


Figure 6 Schematic of telescoping tank concept with SMA locking ring joint (a) deployed and undeeployed positions; (b) cross section of typical segment (c) detail of joint geometry

Deployment of the telescoping structure must be addressed if a telescoping tank structure is to be developed. Gas pressure alone will only be adequate for deployment purposes if a bladder is used inside the tank, because the other seal types are only effective following engagement. Locking rings, whether conventional mechanical systems or the SMA type will require proper positioning of the tank before they can be correctly engaged. Keeping the thin-walled tank segments properly shaped throughout the flight and landing environment such that the locking rings will be properly engaged is a substantial problem. The success of face seals on the mechanical back-up structure likewise depends on correct alignment during deployment, which is particularly challenging given the large diameter of the tank. Based on these concerns it is apparent that additional structure may be required to ensure correct deployment and positioning of the tank.

6 CONCLUSIONS

Long term storage of liquid oxygen on Mars can be effectively and efficiently developed based on existing technology. An inflatable tank concept using redundant fiber-reinforced Teflon FEP bladders to contain the cryogen is recommended. This is an efficient, lightweight option requiring no extra systems for deployment or sealing. The support structure is the highest mass portion of the structure. A ring girder support configuration supported externally by a truss structure and spacecraft legs is proposed for the support structure, though optimization of this structure can be used to develop a more efficient design. Prototype and development work in several areas is needed to ensure the success of such a design. Chief among the needs is for the demonstration of the durability of the proposed bladder design for the liquid oxygen environment, particularly with respect to permeability.

Telescoping tank concepts can be produced for the Mars liquid oxygen tank. However, the overhead associated with forming effective joints and extra weight associated with greater mass of the pressure wall segments, systems to maintain proper alignment of joints during deployment, and electrical or mechanical systems needed to engage joints represent inefficiency as compared with the inflatable tank concepts presented above. If telescoping design concepts are pursued, additional work in joint technology is needed, including development of oxygen compatible inflatable seals for sealing around the hoop direction; verification of the SMA locking ring concept; and evaluation of the sealing performance of a SMA locking ring.

Detail design work is needed before application of the design concepts in this report should proceed. Some fundamental choices should be addressed, including whether it would be more effective to use multiple smaller tanks rather than a single large tank, as proposed here. Also, while a cylindrical tank shape was considered in this report, the shape of the tank should be optimized based on specific mission requirements and launch vehicle specifications.

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